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# APPLICATION OF MILLIMETER WAVE, EDDY CURRENT AND THERMOGRAPHIC METHODS FOR DETECTION OF CORROSION IN ALUMINUM SUBSTRATE (Preprint)

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**14. ABSTRACT**
Aluminum structures exposed to the elements are susceptible to corrosion. Corrosion may cause various mechanical and structural deficiencies such as material thinning. It is desirable to rapidly detect and evaluate the properties of an aluminum substrate early in the corrosion process to avoid costly maintenance actions later. There are several nondestructive, testing methods for this purpose. To investigate capabilities of millimeter wave, conventional eddy current, and flash thermography techniques for detection of large corrosion areas in aluminum substrates, two corroded samples were inspected with and without dielectric coating (appliqué). This paper presents the results of the c-scan imaging of these samples using the methods mentioned above. The attributes of these methods for detection and evaluation of large, severe and non-uniform corrosion areas with and without a dielectric coating are discussed.

**15. SUBJECT TERMS**
aluminum substrate, corrosion, dielectric coating, nondestructive testing and evaluation, millimeter wave, thermography, eddy current

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# APPLICATION OF MILLIMETER WAVE, EDDY CURRENT AND THERMOGRAPHIC METHODS FOR DETECTON OF CORROSION IN ALUMINUM SUBSTRATE

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**ABSTRACT.** Aluminum structures exposed to the elements are susceptible to corrosion. Corrosion may cause various mechanical and structural deficiencies such as material thinning. It is desirable to rapidly detect and evaluate the properties of an aluminum substrate early in the corrosion process to avoid costly maintenance actions later. There are several nondestructive testing methods for this purpose. To investigate capabilities of millimeter wave, conventional eddy current, and flash thermography techniques for detection of large corrosion areas in aluminum substrates, two corroded samples were inspected with and without dielectric coating (appliqué). This paper presents the results of the c-scan imaging of these samples using the methods mentioned above. The attributes of these methods for detection and evaluation of large, severe and non-uniform corrosion areas with and without a dielectric coating are discussed.

**Keywords:** aluminum substrate, corrosion, dielectric coating, nondestructive testing and evaluation, millimeter wave, thermography, eddy current.
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## INTRODUCTION

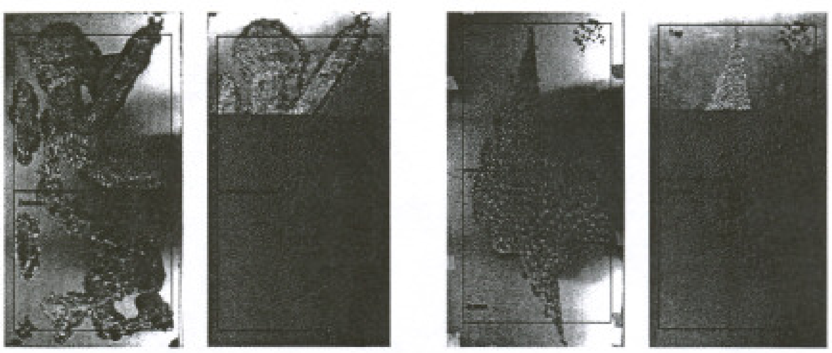
There are many military and civilian aviation aluminum structures that are susceptible to corrosion, causing various structural deficiencies such as material thinning. Corrosion mitigation and remediation cost is estimated in the billions of dollars [1]. Damage tolerance approach (vs. find-it and fix-it) can be expedited via timely detection of corrosion [2]. In most practical cases aluminum structures are covered with paint or other dielectric coating, so that visual detection of corrosion becomes difficult. Therefore, it is very important to detect this corrosion under the paint without having to remove the paint or coating. There are several nondestructive testing and evaluation (NDT&E) methods for this purpose [3]. They have demonstrated good results and capabilities for detecting and evaluating localized corrosion severity. However, there is no single method that satisfies all requirements. Moreover, data fusion possibilities of applying different

NDT&E methods are also important issues which are increasingly being considered in many NDT applications [4].

In this investigation millimeter wave, eddy current and thermographic methods were used to image two severely corroded aluminum substrates with and without dielectric coating (appliqué). Appliqué is a thin polymer which is used in the place of paint to simulate its effect on measurements since its dielectric properties are similar to those of paint. Obtained images were used to determine the attributes of each method for this purpose.

## SAMPLES DESCRIPTION

Two 13" by 27" aluminum panels with a thickness of 0.125" were used in this investigation. Both panels had been severely corroded in a salt-fog chamber, and Figure 1 shows the pictures of the corroded panels, with and without appliqué. The corroded regions in these panels were locally different in shape (i.e., spatial boundaries) and severity as can been seen in the left pictures of Figure 1. The relative level of corrosion severity in each of these panels was equivalent to over 20% material loss based on conventional eddy current data. After these panels were scanned with the corrosion exposed, two sections of the panels were covered with one to two layers of appliqué as shown in the right pictures of Figures 1a and 1b. Appliqué thickness was 0.010" and 0.005" for the lower section (approximately the lower 1/3 of each panel) and the middle third section, respectively, while the upper section (about the top 1/3 of each panel) was left exposed. Since these panels were large in addition to the fact that the corrosion was not uniform throughout, they were not exactly flat (i.e., possessing a slight curvature). Consequently, when performing the millimeter wave imaging, the panels were attached to a thicker and flatter aluminum substrate using double sided tape to ensure a flat surface for scanning. As the series of scans were completed, the sample had to be reattached to the substrate again because the double sided tape would release and allow the sample to rise off the substrate.



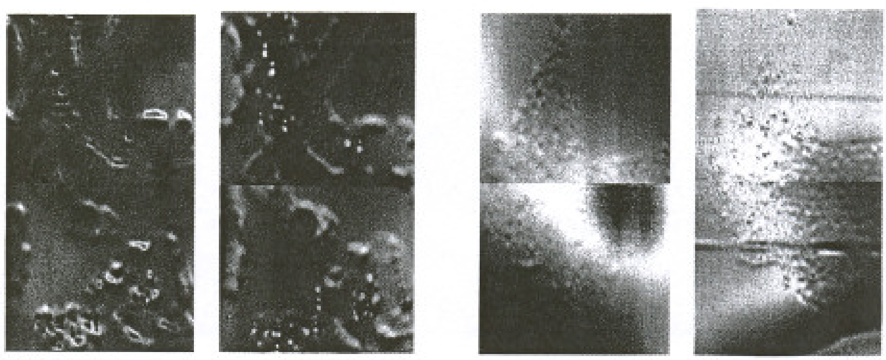
(a) (b)

**FIGURE 1:** Pictures of panel: (a) #1 and (b) #2 before (left two) and after (right two) appliqué was applied. Two millimeter wave scanned areas are marked by the solid lines.

## NEAR-FIELD MILLIMETER WAVE METHOD

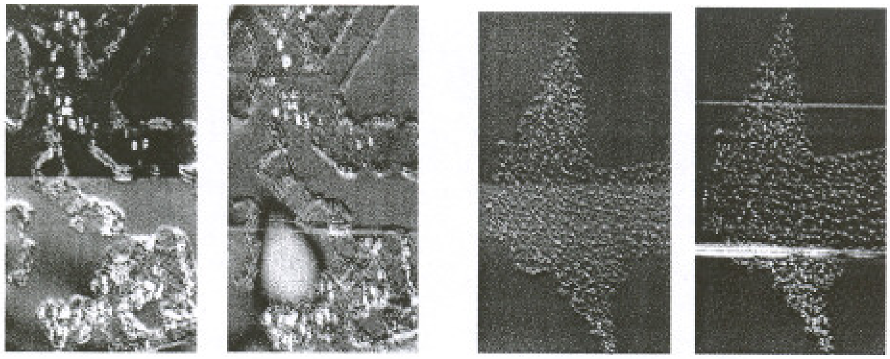
Millimeter waves are electromagnetic waves with a wavelength between 1 and 10 millimeters and corresponding frequency of 30 GHz to 300 GHz [5]. Millimeter waves can penetrate through low-loss dielectric materials such as paint, appliqué and corrosion byproducts [6]. Near-field millimeter wave techniques are sensitive to distance variations at the boundary interfaces and dielectric property variations making them very attractive for the detection of corrosion under dielectric coating [6-8]. These techniques do not require contact (and therefore a couplant) between the millimeter wave probe and the sample under test. The distance between the aperture of open-ended waveguide probe and the sample under test is referred to as the standoff distance (or liftoff). These techniques are portable, inexpensive, small, easily incorporated into existing scanning platforms. They may provide on-line and real-time imaging and frequency, polarization and probe type diversity and optimization [6]. Near-field millimeter wave NDT&E techniques, utilizing open-ended rectangular waveguide probes, have been successfully used to detect the presence of corrosion product under paint and primer in both steel and aluminum substrates [6-10]. In addition, these techniques have been successful in detecting and evaluating corrosion precursor pitting under paint [11-15]. For this purpose, a novel differential probe utilizing two open-ended waveguide apertures was designed, built and successfully applied for detection of corrosion precursor pitting [13-15]. The output of this probe represents the coherent difference between the reflected signals picked up by each aperture. Since the two apertures are closely spaced, both of them face an equivalent amount of standoff distance change. Therefore, the output of the differential probe is not as significantly affected by changes in this parameter as a single probe would [13-15]. Millimeter wave images of large corrosion areas presented in this paper were obtained using the differential probes at Ka-band and V-band.

Figures 2 and 3 show the millimeter wave images of panels #1 and #2 obtained using the differential probes at 33 GHz (Ka-band) and 67 GHz (V-band), respectively. The horizontal line across the middle of the images is an artifact since two separate images (top and bottom) were augmented. The corrosion areas with sharp boundaries are clearly visible in the images of the panels. Moreover, variations in corrosion severity are



(a) (b)

**FIGURE 2**: Millimeter wave images of panel: (a) #1 and (b) #2 before (left two) and after (right two) appliqué was applied at 33 GHz.



(a) (b)

**FIGURE 3**: Millimeter wave images of panel: (a) #1 and (b) #2 before (left two) and after (right two) appliqué was applied at 67 GHz.

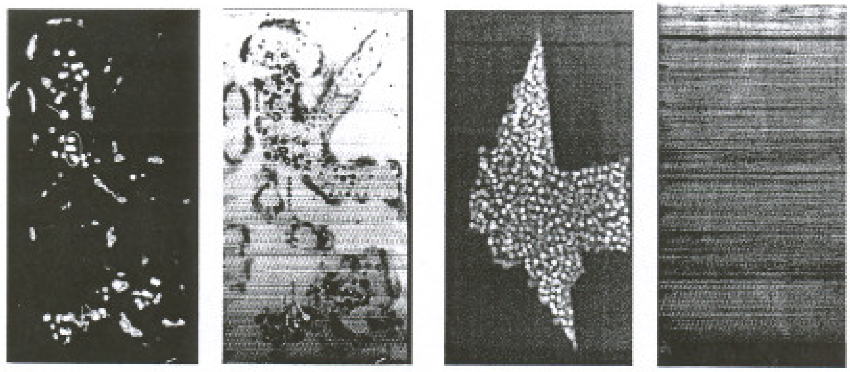
also clearly seen in these images. It is expected that at higher frequencies more features of the corrosion areas are to be detected. To this end, boundaries are sharper and non-uniformities of the corrosion areas more visible in the 67 GHz images (Figure 3) than in the 33 GHz images (Figure 2b) which are the direct results of using a higher frequency, as expected. The blurry portions of the 33 GHz images of panel #2 (Figures 2) are caused by a bulging effect between the panel and the supporting substrate due to the double sided tape releasing as mentioned early.

The corresponding images of the panels when covered with appliqué are very similar to those without appliqué. As is evident from Figures 2 and 3 there is no difference between areas with different thickness of appliqué, and only the boundaries of the layers of appliqué are clearly visible. The top and bottom horizontal lines on the image of panel #2 (Figures 2b and 3b) show the boundary lines for the sections with different appliqué thicknesses. It should be noted that there are no indications of these boundary lines in the image of panel #1 at 33 GHz (Figure 2a, right image) and only the bottom line can be seen in its image at 67 GHz (Figure 3a, right image). The former case is an indication of some delamination of the appliqué from the sample. The latter case can be explained by the lower sensitivity and spatial resolution at lower frequencies.

In summary, millimeter wave NDT&E techniques show great potential for detection and evaluation of relatively severe and non-uniform corrosion areas in aluminum substrates. This is particularly true for structures covered with dielectric coatings (e.g., appliqué), in which millimeter wave signals can easily penetrate through the coating and expose the presence of corrosion.

## EDDY CURRENT METHOD

The principles of conventional eddy current are well established and have been used for many years for aircraft inspections. Eddy currents are formed by an alternating electrical current in a coil gives rise to a variable magnetic field. An adjacent conductor (test sample) opposes the effect of the varying magnetic field, and causes an eddy current flowing in a closed loop in the surface of the test sample. This opposition causes a back electromagnetic force in the coil which is detected. Any cracks or discontinuities will



(a) (b)

**FIGURE 4:** Eddy current of overall scan images (right) and liftoff component images (left) of panel: (a) #1 and (b) #2 without appliqué obtained from the back (substrate) side at 6 kHz and 8 kHz, respectively with scan resolution was 0.02".

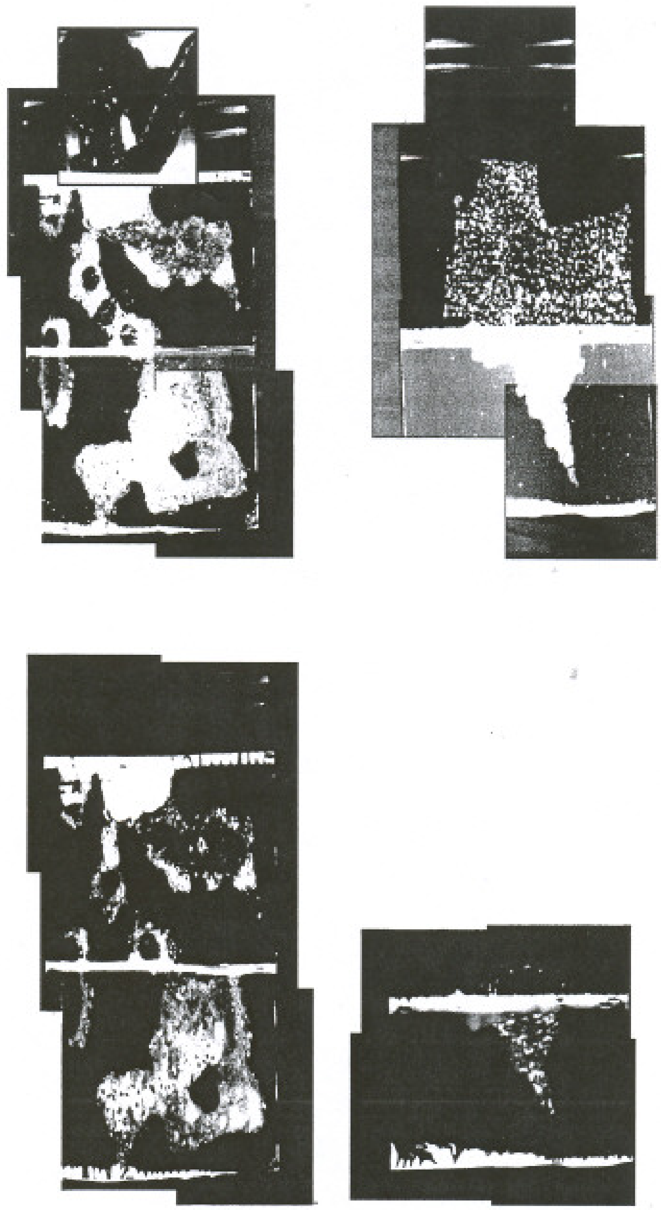
modify the eddy currents generated in the test sample, therefore, altering the back electromagnetic force.

The eddy current c-scan data was taken with the Boeing – Mobile Automated Scanner (MAUS-IV). The eddy current system scanned a standard aluminum plate of similar conductivity and thickness to the samples with milled out areas that represented 10, 15, and 20% material loss. The scans of the standards are not shown in the figures, however it was determined that corrosion in the samples was over 20% material loss. The step size resolution was 0.020". Figure 4 shows the images of the panels without appliqué obtained using eddy current techniques at different conditions. The eddy current images were obtained from the back side (through the panel) of the samples at 6 and 8kHz, respectively, because a high frequency probe (approximate range of 200 – 500 kHz) was not available for testing.

## THERMOGRAPHIC METHOD

The basic principles of thermography center around thermally exciting a surface of a test sample by heating it, and using an infrared camera to monitor changes in the surface temperature. Any subsurface defects obstruct the diffusion of heat from the surface into the sample's interior and affect the cooling behavior of the nearby points on the surface [16].

Figure 5 shows the infrared images of the panels when covered with appliqué obtained using the thermographic techniques applied from their front (appliqué – corrosion) side at different times after thermal excitation. The images were taken at different times because of the different thermal properties of the samples containing portions without appliqué, one layer, and two layers of appliqué. The thermographic analysis was qualitative and no corrosion measurements of material loss were made with this method for this study.



(a) (b)

**FIGURE 5:** Infrared images of panel: (a) #1 and (b) #2 with appliqué obtained from the front (appliqué – corrosion) side using the thermographic method at 0.3 s (upper two) and 1.034 s (lower two, the image of the portion of panel #2 is shown) after thermal excitation. The image of the untaped region of panel #1 located in the upper-left image at the top center position scaled different than the rest of image.

## SUMMARY

The inspection of dielectric-covered aluminum substrates for the purpose of detection of relatively large and non-uniform areas of corrosion was considered in this investigation. For this purpose, two aluminum panels were corroded in a salt-fog chamber

yielding a corroded surface that was locally different in shape and corrosion severity. The relative level of corrosion severity in each of these samples was over 20% material loss based on the conventional eddy current results. Two sections of corroded surface of each sample then were covered with appliqué at thicknesses of 0.005" and 0.010", respectively. Three NDT&E methods including near-field millimeter wave, eddy current and thermographic methods were utilized to obtain images of the panels. The attributes of each technique for this application can be summarized as follows.

The millimeter wave method provides for the detection of corrosion through dielectric coating (paint) with high spatial resolution and frequency, polarization and probe type diversity and optimization capabilities. This is a non-contact method that is sensitive to corrosion severity and does not require a couplant. The use of differential millimeter wave probes provides compensation for liftoff change. This was qualitatively verified in the corrosion panels with appliqué by the eddy current and thermography data. In addition, near-field millimeter wave techniques are portable, inexpensive, small, easily incorporated into existing scanning platforms. However, millimeter wave techniques cannot detect through metals.

Conventional eddy current methods have been widely accepted for use in corrosion detection for many years. These techniques are contact, but have high spatial resolution and sensitivity to corrosion severity. They are portable, inexpensive, small, on-line and real-time, widely used on many existing systems, and can detect through metals at small depths.

The flash thermography method is also a non-contact with high spatial resolution. It is sensitive to corrosion severity and other discontinuities. Thermography is a rapid technique and ideal for composites and polymer coatings.

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